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Sediment, Erosion and Water Intake in Furrows

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Summary. Observations and studies were conducted on the origin and destination of sediment in irrigation water, and the effects of sediment adsorbed on the wetted perimeter of furrows on water intake and erosion. Fine sediment adsorbed on the perimeter reduced intake and increased soil water tension which was the primary mechanism holding the sediment on the perimeter. This self enhancing effect causes this thin seal to decrease erosion and intake rates. In contrast, removal of a few square centimeters of this seal by chance events after water velocities and shear forces have increased often causes reduced tensions, exfoliation of the surface seal and erosion pits which develop into head cuts.

Origin and Destination of Sediment in Irrigation Water

Irrigation water supplied to furrows may be sediment laden or nearly clear, depending on its origin. Runoff, resulting from intense rains or rapidly melting snow, carries sediment into rivers. Irrigation systems carrying water directly from these rivers to farms can deliver significant amounts of these sediments to the farmer's supply ditch. When these supply ditches are kept free of grass and weeds, most sediment will pass through the supply ditch into the furrows. Where grass and weeds are growing on the bottom and sides of the ditch, most sediment settles out, requiring periodic removal by the farmer. In contrast, when water for irrigation is pumped from wells, or when surface water resides in a reservoir for appreciable time periods, the water delivered to the farmer's supply ditch may be nearly sediment free.

A large part of the suspended sediment in furrow streams is generated by action of the water after it enters the furrow. Rapid wetting of dry clods and large aggregates in the furrow perimeter traps pockets of air within them. Water surrounding the aggregates compresses the air as the water is drawn toward the aggregates centers by capillarity. At the same time, the water dissolves some of the materials which bind the aggregate together. Eventually, pressure of the compressed air exceeds the cohesive strength of the bonds between particles and the air explodes the aggregates. A similar process disintegrates clods into small aggregates which contribute to the bed load.

Near the water supply end, furrow flow rates are high and the water is often clean. Under these conditions erosion takes place over the entire wetted furrow perimeter as shear forces, resulting from the flowing water, pull aggregates away from the weakened clods. Surface soil on the furrow bottom is wetted quickly as water flows over it. Soil on the furrow sides wets more slowly by capillarity. Consequently, clods and aggregates in the furrow bottom are more rapidly disintegrated. However, soil on the furrow sides, in addition to the water shearing forces, is affected by gravitational force. Our observations indicate that the combined effect of these forces is to cause initial rates of erosion on the sides and bottom of the wetted perimeter to be approximately equal. As erosion over the entire wetted perimeter proceeds, the furrow sides above the wetted perimeter are undercut and the overhanging soil, wetted by capillarity, breaks from the furrow bank, falls into the furrow and is quickly broken into small aggregates by its fall and by the shearing action of the flowing water. Soil eroded from the furrow bottom lowers the bed level and water surface. This limits the time for which water can erode any specific level on the furrow side. Consequently, long-term furrow erosion tends to excavate soil primarily downward until more cohesive soil layers such as an old furrow bed or plowpan are reached. Most eroded soil, having been reduced to small aggregates, contributes to the downstream bed-load.

The following observations were on Portneuf soil, with sand, silt, and clay contents of about 20%, 60%, and 20%, respectively. This loess soil, common in the Snake River Valley (Idaho, USA) is highly erodible as is generally the case with soils high in silt and low in clay.

Field observations indicate that when furrow slope exceeded 1%, head cuts often developed. These miniature waterfalls drop water one to 10 cm from the existing furrow bed elevation to a lower level, which may be the original furrow bottom before cultivation, or a cultivation pan, where the soil cohesion is high. Kinetic energy, gained by this dropping water, breaks aggregates loose from the impact zone. This undermines the overlying soil which then breaks loose and is quickly disintegrated into small aggregates by the turbulent water in and near the impact zone.

These in-furrow processes often produce massive amounts of bed-load aggregates which roll and bounce along the furrow bottom until they find a resting place sheltered from the shear forces exerted by the flowing water. For most bed-load, this resting place is in the furrow bottom. In the mid-sections of many furrows, erosion from the sides and deposition in the furrow bottoms occur simultaneously and the channels commonly become wider and shallower. Aggregates, swept over the downstream edge of the flat deltas on the furrow bottoms are pulled in against the deltas by the back-washing current (e.g., see Brown et al. 1986) so effectively that there is often no observable bed-load moving past these growing deltas.

Bed-load also settles in furrow sections where slope and water velocity decrease. Sediment often accumulates in such sections until it fills a cross section of the entire furrow. As a result, the irrigator loses control of the water which washes over the furrow ridge and often moves cross-slope, joining flow from similar furrows until it reaches a low area where combined flow of the streams can keep the bed-load moving. Accumulation of such flows from several furrows also causes erosion if the furrow slope increases further down the field.

While the bed-load aggregates bounced and rolled from their points of origin to their points of rest, they abraded small particles from their own perimeters and from the channel bed. These particles were so small that their settling velocities were low compared to the upward eddy velocities of the turbulent stream flow which kept them in suspension. Thus, while the bed-load was rolling, it was contributing to and increasing the suspended sediment.

Some of this fine sediment was observed to adhere to the downstream wetted perimeter of the furrow where water was being absorbed into the soil. Cohesive forces between these soil particles in water saturated systems are extremely small (Kemper et al. 1987). Consequently, the primary force which holds this fine sediment on the soil surface, against the shear force of the flowing water, is probably surface tension force pulling water into the dry soil which is transmitted to these particles on the wetted perimeter via soil water tension. When water which contained significant amounts of suspended sediment entered the furrow and massive erosion did not begin, a thin coating of the fine suspended material was absorbed on the wetted perimeter and became observable within a few minutes.

Eisenhauer et al. (1983) reported that increasing flow rate caused decreased water intake rate and increased sealing of a sandy loam under carefully controlled laboratory conditions. Apparently their higher flow rates were more effective in stirring the sediments and arranging them into a more dense and less permeable condition.

A large portion of the suspended sediment that is not adsorbed on furrow surfaces leaves the furrow with the runoff water. Brown and Kemper (1987) found that most of the clay eroded from the upper reaches of a furrow left the furrow when the runoff rate was 30% or more of the furrow supply rate. Berg and Carter (1980) observed that about half of the water supplied to farmers' furrows ran off. In

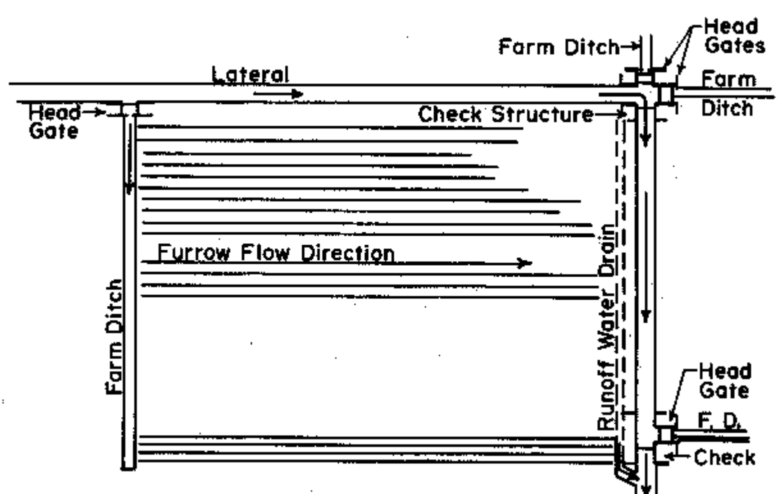

Fig. 1. An example of how runoff is returned back into the system

the Twin Falls Canal System (Idaho, USA), about 70% of the runoff water is directed back into the supply laterals in a manner similar to that indicated in Figure 1. Consequently, the suspended sediment in water supplied by such a system at a specific outlet can vary from practically zero to over 0.2 g/kg water, depending on the sediment content of the runoff water from upstream farms.

Given this sediment range in the supply water, users and canal system operators question whether sediment should be removed from irrigation supply water via settling ponds, etc., before returning it into the delivery system. The following study was designed to help answer this question by determining the effect of sediment in the water on water intake and erosion rates.

Experimental Procedures

Field test sections in Portneuf silt loam (*Durixerollic Calciorthid*) were selected which had slopes of 0.007, 0.012, and 0.040 m/m. Four furrows through these test sections were studied on each slope. Two furrows in each test section were supplied with sediment enriched water and two were supplied with clean water. Data discussed are averages of two furrows for each treatment replicated twice or effectively four replications. The 30 m long test sections began 30 m from the heads of the furrows.

Water from the irrigation pipeline was relatively sediment-free (clean), containing less than 0.2 g sediment/kg water. This supply was delivered to test furrows via tubing, plastic lined basins and small flumes, connected in series (Fig. 2). Water from the same pipeline was enriched with sediment for the other two furrows by

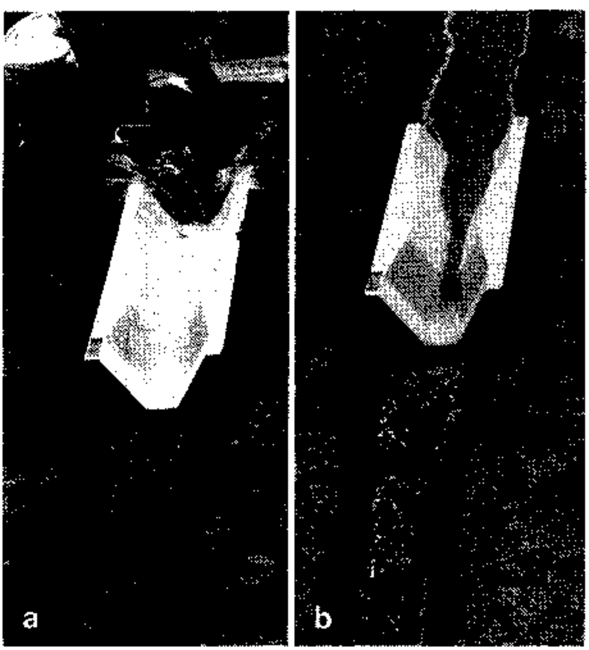

Fig. 2a and b. Arrangement of flumes, pipes, and furrows for supplying and measuring water and sediment. (**a**) "Clean" water supply, (**b**) "Sediment enriched" water supply running it through the top 30 m furrow sections which preceded the test section. Examples of "clean" and "sediment enriched" water passing through flumes are shown on the left and right side, respectively, of Figure 2. Flow rates were measured with long-throated V flumes and adjusted with valves on the supply line until the flow rates to all four furrow sections were equal within ± 10%. One-liter samples of the inflow and outflow water were taken at various time intervals at the bottom lip of the flumes. The sediment in these water samples was filtered through pre-weighed 24 cm Whatman # 50 hardened filter papers, dried, and weighed. Total sediment passing these flumes, and similar flumes at the bottom ends of the 30 m or 60 m long test sections, was calculated by reading the flume flow rate immediately prior to taking the sediment-water sample and multiplying flow rate by sediment concentration and the time interval.

Tensiometer sensors, made of porous ceramic cups 6 cm long and 0.8 cm in diameter, were inserted into the soil about 5 m downstream from the flumes into the test section and 5 cm from the edge of adjacent "clean" and "sediment enriched" furrows when the wetting zone had progressed that far. The center of the porous cup was at a level approximately equal to the initial water surface in the furrow. The mercury column heights in the attached manometers which were attained when the sensors were lying in the flowing water in the furrow adjacent to the planned point of measurement prior to insertion in the soil, were used as zero tension reference.

Results and Discussion

Soil water intake in the test section on the 0.007 slope was generally lower from furrows carrying sediment enriched water than from the furrows carrying clean water (Fig. 3). The percentage difference increased with time. Extent of the wetted

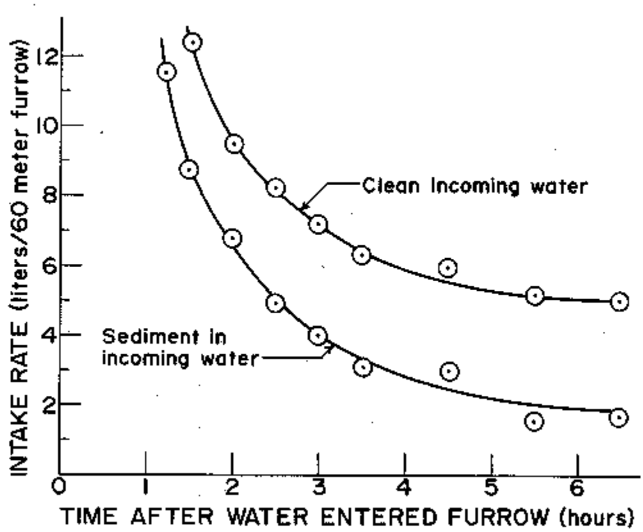

Fig. 3. Intake as affected by sediment in the water in furrows with 0.007 slope

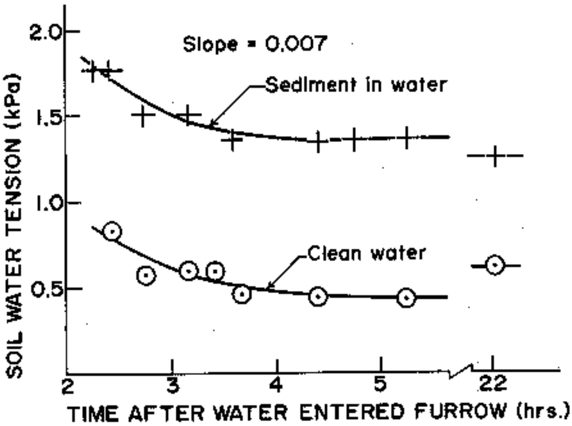

Fig. 4. Tension in soil water 5 cm from the furrow on a slope 0.007

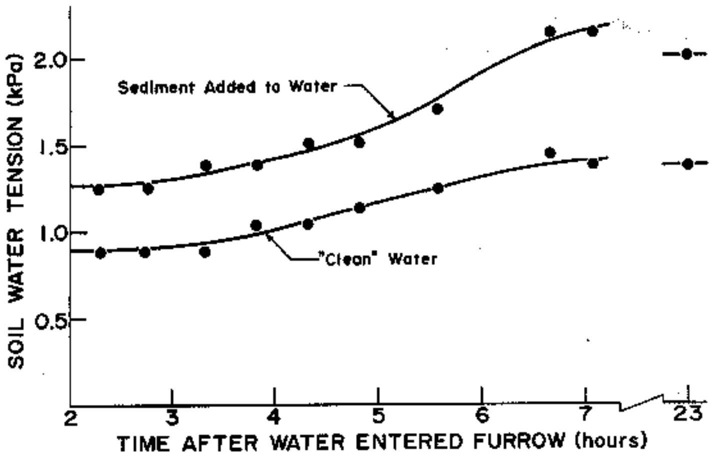

Fig. 5. Tension in soil water 5 cm from furrows and 7 m from the top of the test section with 0.012 slope

soil adjacent to the furrows in the test section indicated much more water absorption at the top end of the furrows where clean water was being supplied than at the bottom end. As the initially clean water flowed down the furrow it picked up fine sediment, some of which adsorbed to the wetted perimeter in the lower portions of the test section. This adsorption of fine sediment on the wetted perimeter in the lower reaches of the test section caused the observed decrease in water intake rates in those reaches. Similar findings are reported by Sharma et al. (1981).

Tensiometers placed about 5 m from the top of the test section showed only about 0.5 kPa tension 5 cm from the furrows with clean water (Fig. 4). Soil water tension was about 1.4 kPa next to furrows in which the water had been enriched with sediment. The greater tension next to furrows with sediment enriched water resulted from the thin coating of fine sediment which was visible on the wetted soil perimeter. This seal coating was only a fraction of a millimeter thick at the end of the irrigation and was probably thinner than that in the first 3 h of the irrigation.

Fig. 6a and b. Looking upstream at furrows on 0.012 slope 3 h after water entered the furrows. **(a)** "Clean" water supplied at top but has picked up appreciable sediment in 6 m, **(b)** "Sediment enriched" water enabled this furrow to resist erosion

Apparently a tension drop of 0.5 to 1.0 kPa occurs across this seal coating, which grades into the original soil in the wetted perimeter within a millimeter. This tension gradient force holds the fine sediment particles on the surface against the shear forces of the moving water and helps stabilize the wetted perimeter against erosion. After a 20 h irrigation, tensions adjacent to the furrows with and without sediment enrichment were still appreciably different. However, by that time particles which were adhering to the wetted perimeter of the furrow section upstream from the test section with less force than the shear forces exerted by the water, had been carried away. Consequently, water entering both types of furrows was free of appreciable sediment. This indicates that under these low slope conditions, even though there was not a continuing supply of sediment, tension in the soil water behind the sealing film was sufficient to hold enough fine particles in the seal to keep tensions relatively high.

Soil water tension about 6 m from the top of the test sections on 0.012 slope and adjacent to furrows with both "clean" and "sediment enriched" water increased with time (Fig. 5). This increase could be explained for the sediment supplied furrows in terms of the seal becoming more complete with time as additional clay particles were adsorbed over the more permeable parts of the seal coat (Fig. 6b).

The lesser, but significant, increase in soil water tension near the clean water furrow was probably a result of the "clean" water containing about 0.2 g sediment/kg water when it entered the furrow in addition to that picked up as it traveled 6 m from the top end of the test section to the tensiometers. Erosion stripped away chunks of the wetted perimeter during the first 2 h preventing accumulation of appreciable amounts of sediment on that perimeter. However, 3 h after water entered the furrow (Fig. 6a) the bed had become deeper and broader decreasing the specific energy and sediment transport capacity of the stream. Easily eroded material had washed out leaving more cohesive material in the wetted furrow perimeter which stayed in place for extended time. Clay platelets drawn into the larger pores, or adsorbed on the most porous surfaces probably helped reduce water intake rates and caused the observed increase in the soil water tension. The soil surface on the furrow perimeter was held tighter so the flowing water was less able to pull units of the soil surface loose and carry them away. Extensive erosion had already taken place in the "clean water" furrow (Fig. 6 a) while the "sediment enriched" furrow (Fig. 6 b) was still practically intact.

Soil water tension 7 mm from the top of the test section adjacent to the clean water furrows on the 0.04 slope continued to drop for the first 3 h and then remained practically constant (Fig. 7). During the first 3 h the furrow bed was rapidly eroded to about 8 cm below the original furrow bed (Fig. 8 a). Although the erosion rate decreased, rapidly moving water in these steep furrows apparently kept stripping away particles before they could form a seal. The absence of seal formation prevented a rise in soil water tension and the subsequent increase in forces that would have held more particles on the surface and would have bound the surface more tightly to the underlying soil.

Soil water tension near the sediment enriched furrow was again higher than in its clean water counterpart. The sealing film had obviously started forming during the first ½ h. This seal coat became more visible with time. 90 min after the irrigation started, measured sediment removal from this furrow section was decreasing and soil water tension at the sensor was holding constant. About this time, a small head cut began to form about 1.5 m downstream from the sensor. This head cut dropped the water surface about 3 cm and moved upstream about 1.4 cm/min. It destroyed the surface seal as it traveled. When the head cut was 20 cm downstream from the tension sensor, the manometer started to drop (Fig. 7).

Passage of the head cut deepened the furrow by erosion and lowered the furrow water level about 3 cm, which normally would have increased soil water tension at the sensor. However, since the drop in water surface occurred at the time the surface seal was destroyed, the drop of the water surface just reduced the drop in tension. In other words, if the surface seal had been destroyed without dropping the water surface, the tension drop in the top line of Figure 7 would probably have been about 1.3 kPa instead of 1.0. After the head cut passed the sensor and was 20 cm upstream, the manometer indicated that soil water tension at the sensor had passed its minimum value and was increasing. Figure 6 b shows the head cut about 20 cm upstream from the tensiometer in the furrow with "sediment enriched" water. The head cut's passage eroded the "sediment enriched" furrow about 3 cm which was less than the 8 cm erosion which took place in the "clean water" furrow (i.e., Fig. 8 a). In the "sediment enriched" furrow there was no observable erosion above the head cut (Fig. 8 b) except for near the edge of the head cut where flakes of the sealing surface were being pulled off. The decrease in soil water tension near the head cut reduced the force holding the sealing surface to the soil.

Generally, furrows carrying "sediment enriched" water on these slopes (i.e., 0.007 to 0.040) developed seal coats which reduced intake 40% to 60% compared to furrows with "clean water." When low slopes or limited flow rates precluded the initiation of head cuts, erosion from these furrows carrying sediment enriched water was negligible. When furrows on 0.04 slopes were supplied with sediment enriched water, head cuts developed only when "sediment enriched" furrow flows exceeded 6 l/m. On 0.012 slopes, head cuts developed only when "sediment enriched" furrow flows exceeded 14 l/m. On 0.007 slopes, head cuts were not observed in furrows receiving sediment enriched water at furrow flow rates up to 20 l/m.

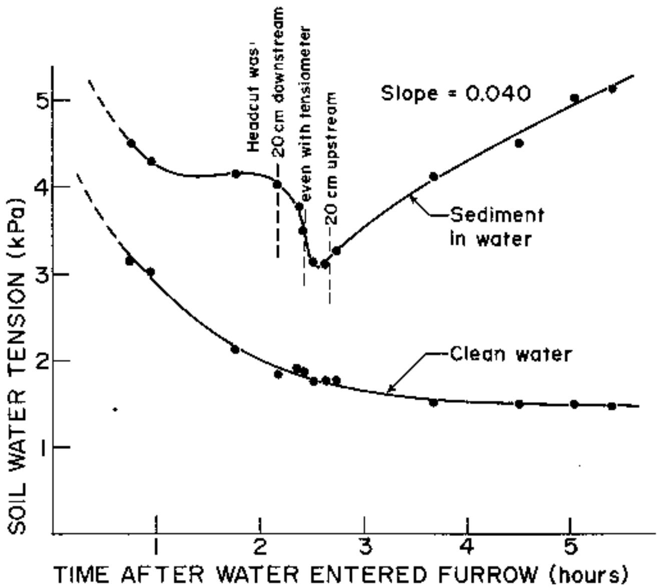

Fig. 7. Soil water tensions 5 cm from furrows on a 0.04 slope

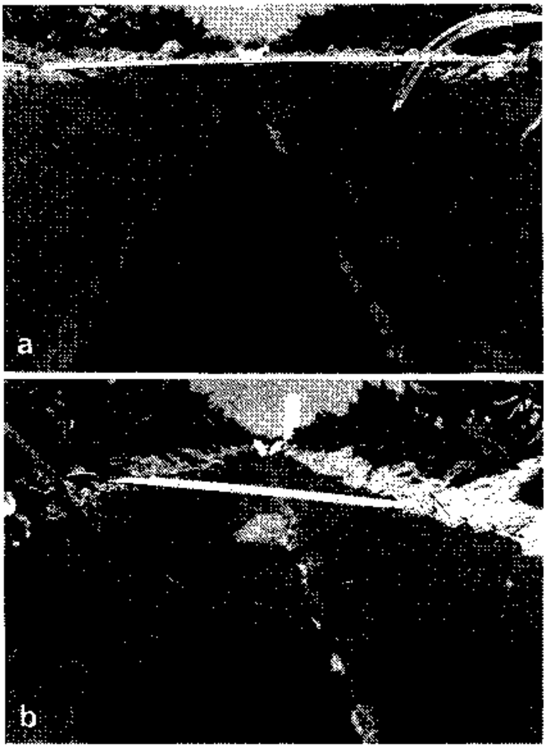

Fig. 8a and b. Looking upstream at furrows on 0.04 slope after 3.7 h of irrigation with furrow flow rates of 6 l/m. **(a)** Furrow condition about 7 m from the top where clean water was supplied. **(b)** Furrow condition about 7 m from the top where sediment enriched water was supplied and a head cut developed

The fine sediment seal held on the furrow perimeter by the soil water tension gradient tends to increase the tension which holds it and is often a self enhancing phenomenon. However, the same phenomena can be reversed, especially when the water has ceased to carry appreciable sediment.

Occasionally, clods supported precariously on the furrow shoulder had their support weakened as the soil became wetted by capillarity. As a result, these clods rolled into the furrows and often broke portions of the seal from the wetted furrow perimeter. This reduced the tension in the vicinity of the damaged section and the seal began to flake away in the flowing water. (A video of this and related processes was made by the authors.) As the unsealed area grew, water entered the soil more readily and the tension holding the soil against removal by the flowing water was further reduced. As additional seal was removed, the underlying soil began to erode and miniature scour holes or "scooped out" sections formed. Initially, these grew slowly. The head loss or drop in the water surface elevation along the erosion pockets was small because the flow cross section was large. As the process continued, the erosion pocket lengthened and the decreasing water surface elevations at the upstream edges of the erosion pockets were appreciably lower than the water running over the original bed. This resulted in small waterfalls whose elevation drops grew with time. Increasing turbulence generated by the increasing drop at the waterfalls resulted in accelerated erosion and undercutting which caused the head cuts to move rapidly upstream. There are undoubtedly other mechanisms which also generate head cuts. In Portneuf silt loam soil, local removal of the surface seal and the processes described above appeared to start many of the head cuts observed in later stages of irrigation.

Conclusions and Applications

The top end of most furrows in Portneuf silt loam soil supplied with clean water, will have water intake rates 50% to 100% higher than those sections downstream where erosion and abrasion of aggregates has incorporated appreciable sediment in the flowing water and some of that fine sediment has adsorbed onto and helped seal the wetted perimeter. Differences in sediment content along the furrows are more effective than the normal 20% or 30% greater water intake opportunity time at the top end, in causing greater total intake at the top than at the bottom ends of furrows. This higher water intake rate at the top end, resulting from lesser amounts of sediment in water in the first 30 m or 40 m of the furrow, can be largely eliminated by delivering significant amounts of fine sediment in the supply water.

Sediment free water resulted in substantial erosion at furrow flow rates in our studies as low as 8 l/m on 0.04 slope, 12 l/m on 0.012 slope and 15 l/m on 0.007 slope. The seal coat which develops from sediment in the supply water can help reduce erosion at the top ends of fields by: (1) reducing water intake rates so that the flow rate required to enable water to reach the end of a given length furrow is reduced, and (2) by increasing soil water tension force which helps hold the soil on the furrow perimeter and allows higher flow rates before erosion begins.

These facts argue strongly against removing fine sediment from irrigation supply systems and may provide sufficient reason to justify developing means to incorporate fine sediment into the irrigation water when silt loam soils are dominant in the area served by the system. The results reported above are probably not applicable to all soil types.

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